NASA TECHNICAL TRANSLATION NASA TT- 20331

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Toshihiko Yamauchi, Hiroaki Ogawa, Reiji Yamada and Takeshi Fukuda

Japan Atomic Energy Research Institute, March, 1987, 25 pgs, JAERI-M-87-045

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. SEPTEMBER 1988

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JAERI-M 87-045

Design Study for Measurement of Neutral Hydrogen Atom Density by Laser Induced Fluorescence Method

Toshihiko YAMAUCHI, Hiroaki OGAWA, Reiji YAMADA and Takeshi FUKUDA+

Department of Thermonuclear Fusion Research,
Naka Fusion Research Establishment
Japan Atomic Energy Research Institute
Naka-machi, Naka-gun, Ibaraki-ken

(Received February 18, 1987)

It is designed to measure the fluorescence light emitted from the transitions 1S - 2P of L_α line (λ = 1215 Å) or 2P - 3S or 2P - 3D of H_α line (λ = 6563 Å), excited by the laser induced fluorescence method. The signal-to-noise ratio (S/N) is evaluated at the measurement in the parameter ($\bar{n}_e = 10^{12} - 10^{14}$ cm^{-3}, T_e = 10 eV - 1 KeV) of tokamak plasma. The light paths in JFT-2M and JT-60 tokamaks are proposed.

Keywords: Neutral Hydrogen, H_α Line, L_α Line, Laser Induced Fluorescence Method, Signal to Noise Ratio, Tokamak, JFT-2M, JT-60, Plasma Boundary, Plasma Core

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+ Department of Large Tokamak Research

Contents

1. Introduction /1

Measuring of neutral hydrogen atom density in plasma seems to be important not only for consideration of the relationships between the flux of hydrogen atoms and H mode but also for calculation of the fuel supply efficiency of reactors and the combustion rate (Reference 1 and 2). To obtain the neutral hydrogen atom density, there is a method which measures the emitted H_α line or $L\alpha$ line with a photodiode or a photomultiplier tube. This method measures in continuous-time but it is difficult to calculate the spatial distribution and the absolute values accurately. This is because when it is calculated with Abelian transformation, it is significantly influenced by the shape of the area near the plasma and the measurement accuracy of that area and also the density of the center can not be obtained due to the large difference as much as $10^{6-7}cm^{-3}$ between the center and area around the center in the neutral hydrogen atom density. Also the flux of the hydrogen atom can not be measured with this method. There is another method which measures neutral particles emitted from plasma with a charge exchange neutral particles analyzer. This method assumes the spatial distribution of the neutral particles,then calculates the neutral hydrogen atom density with the plasma parameters. A method which does not have the above mentioned weak points is the Laser Induced Fluorescence Method (LIFM) which has the capability to measure in continuous-time. In this method, the laser beam that has a wave length corresponding to the energy width of arbitrary transitions of the hydrogen atom is injected into plasma. Then the atom,excited by the laser beam, emits fluorescent light and the neutral hydrogen atom density is calculated by measuring the change of the emitted light.

This report discusses the case that the signal to noise ratio (S/N),which is an important factor for the measurement of neutral hydrogen atom density by the laser induced fluorescence method with H_α line transitions (λ = 6563Å) or L_α line transition (λ = 1215Å) is applied to tokamak plasma. The past D-III measured deuterium atom density (n_D) of $10^{12}m^{-3}$ (Reference 3) but measurement of hydrogen atom density in the diverter of the ASDEX required much effort (Reference 4). In Japan, Kyushu University is studying LIFM and it has been applied to tokamak plasma (Reference 5).

In this report, the following three subjects are discussed. 1) Fluorescence of H_α line emitted by excited hydrogen atoms at the n=2 level by laser beam. 2) Fluorescence of L_α line in the same manner as 1). 3) Fluorescence of H_α line emitted from the excited hydrogen atoms at the n=3 level by laser beam. To study the S/N of these cases, the fundamental differential equations for calculation of fluorescence is discussed first, and the present apparatus and physical quantity; i.e, laser beam, detector, filter and other optics parts are described and also the plasma parameters are described and lastly, the influence of calibration method of the measurement apparatus and the magnetic field is discussed.

2. Fluorescence from neutral hydrogen excited by dye laser into n= 2→3 level /2

2.1. General

In the case that many hydrogen atoms collide with electrons in the plasma and the atoms are excited by transition from the n=2 level to the n=3 level and return to the low energy level in a short time, light is emitted. When the electron temperature and density in this light (called fluorescence hereafter) are known, the hydrogen atom density can be obtained by H_α line fluorescence measurement. The fundamental experiment with this method was performed by Burakov (Reference 6 and 7). Later, Hackmann (Reference 8) measured hydrogen atom density with a tokamak apparatus and Muller (Reference 3) measured it with a Doublet III.

2.2. Fundamental formulas

The important fundamental formulas for understanding the method are described. At first the following assumptions are made. The excitation from the ground state to the n=2 level and to the n=3 level is only 2 kinds (1 → 2 and 1 → 3). (2 → 3 is neglected because it is small compared with 1 → 3.) The energy density of the incidence laser beam of the H_α line (6563Å) is written u_ν . The polarized light of the incidence laser beam and the fluorescence is negligible (Refer to Appendix B).

The excitation rates, R_{12} and R_{13}, of the transition from level 1 to 2 and from 1 to 3 per unit time are

$$R_{12} = n_e \langle \sigma_{12} v_e \rangle \quad , \quad R_{13} = n_e \langle \sigma_{13} v_e \rangle \qquad 1)$$

The differential equations of each excitation level are

$$dn_2/dt = R_{12}\,n_1 + A_{32}\,n_3 + B_{32}\,\rho(\nu)\,n_2 - A_{21}\,n_2 \qquad 2)$$

$$dn_3/dt = R_{13}\,n_1 - (A_{31} + A_{32})\,n_3 - B_{32}\,\rho(\nu)\,n_3 + B_{23}\,\rho(\nu)\,n_2 \qquad 3)$$

where $B_{23}\,\rho(\nu)$ and $B_{32}\,\rho(\nu)$ are the induced excitation and the induced emission ratio by the laser beam respectively. The explanation for the other symbols is shown in Table 1. The excitation and emission process of the energy in Equation 2) and 3) is shown in Fig. 1. The d/dt in Equation 2) and 3) equals 0 in the equilibrium state. Here, the following 2 cases are considered.

i) The case of $R_{13} = 0$

From Equation 3),

$$n_3/n_2 = B_{23}\,\rho(\nu)/(A_{32} + A_{31} + B_{32}\,\rho(\nu))$$

$$= \frac{g_3\,\rho(\nu)}{g_2 X\,\rho(\nu_0)} \Big/ \left\{ 1 + \frac{\rho(\nu)}{X\,\rho(\nu_0)} \right\} = \frac{g_3}{g_2}\,\frac{S^*}{1+S^*} \qquad 4)$$

where $B_{23} = B_{32} g_3/g_2$, $A_{32} = B_{32} = 8\pi h \nu^3/c^3 = \rho(\nu_0)\tau\gamma g\cdot s\cdot cm^{-2}\cdot \mathring{A}^{-1}$, $\phi_c = \rho(\nu_c)\,\nu^2$.

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Table 1. Explanation of symbols /3

A_{ik} : Natural emission ratio from i level to k level

($A_{32}=4.3\cdot10^{7}$ s^{-1} collision

$=5.4\cdot10^{7}$ s^{-1} no collision

$A_{31}=5.5\cdot10^{7}$ s^{-1} collision

$=0$ s^{-1} no collision

$A_{21}=4.7\cdot10^{8}$ s^{-1} collision

$=6.3\cdot10^{8}$ s^{-1} no collision)

$\rho(\nu)B_{ik}$: Induced emission ratio from i level to k level

$\rho(\nu)B_{ki}$: Induced absorption ratio from k level to i level

W_{ik} : Induced emission (absorption) ratio, $\rho(\nu)B_{ik} + A_{ik}$

$\rho(\nu)$: Laser energy density per frequency, $8\pi h\nu^3/c^3/(e^{h\nu/kT}-1)$

g_i : Statistical weight

($g_1 = 6$

$g_2 = 4$

$g_3 = 9$)

σ_{ik} : Excitation cross section area from level i to level k by electron

V_e : Velocity of electron

V_g : Velocity of atom

R_{ik} : Excitation ratio from level i to level k

m_e : Mass of electron

n_i : Number of atoms at level i at the time of laser irradiation, atoms$\cdot$cm^{-3}

n_{io} : Number of atoms at level i at the time of no laser irradiation

n_e : Electron density

λ : Wave length (λ_o: laser beam incident wave length)

ϕ : Laser irradiation output density J$\cdot$cm^{-2}s^{-1}

I : Laser irradiation output density J$\cdot$cm^{-2}s^{-1}Å^{-1}sr^{-1}

f_{ik} : Oscillator strength for transition from level i to level k

$\Delta\Omega$: Solid angle

Tr : Transmittance of observation system

η : Quantum efficiency

ν : Frequency

ν_0 : Frequency of laser beam

c : Luminous flux

M : Mass of hydrogen atom

T_g : Temperature of hydrogen atom gas

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Also /4

$X = (A_{32} + A_{31})/A_{32}$

$S^* = \phi(\lambda)/(X\phi_0(\lambda)) = \rho(\nu)/(X\rho(\nu_0))$ = Saturation Parameter 5)

$\phi_0(\lambda) = 8\pi h c^2/\lambda^5$ = 123 $W\cdot cm^{-2}\cdot\mathring{A}^{-1}$ = Required laser output for saturation. Intensity of the $H\alpha$ line depends on Equation 4) which is expressed with the saturation parameter. The n_3/n_2 against the saturation parameter is shown in Fig. 2. From the figure, S* is 1.7 at 63% and in the case that the collision dominates (thermal equilibrium at the transitions of 3S,3P and 3D), X is 2.27 otherwise X is 1. For these values, the n_3/n_2 ratio is 0.8 - 0.9 when the laser power of 1 $KW\cdot cm^{-2}\cdot\mathring{A}^{-1}$ is input.

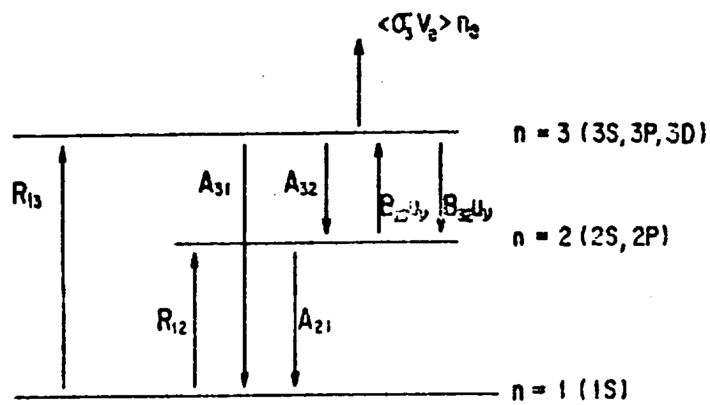

Fig. 1 Excitation and emission process of hydrogen atom at irradiation of L_α line and H_α line

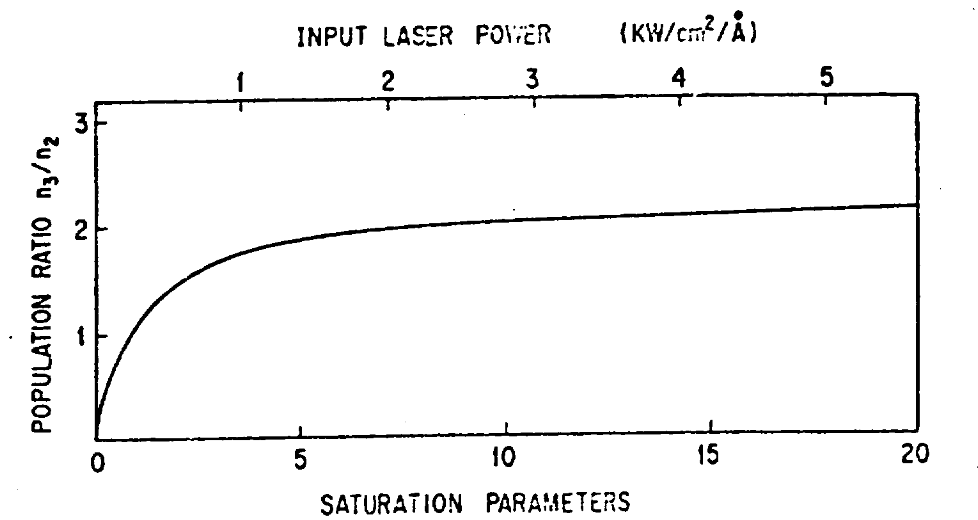

Fig. 2 Excitation particle number against saturation parameter

ii) The case of S*>>1 /5

Under the condition, from Equation 4),

$$n_3/n_2 = g_3/g_2 \qquad 6)$$

When the laser beam is applied, the equilibrium relations between the collision excitation by the electrons and the radiation damping occurs at the n=1 level. Thus

$$n_{10}R_{12}+n_{10}R_{13} = n_2A_{21}+n_3A_{31}$$

and n_3/n_2 is

$$n_3/n_{10} = (R_{12}+R_{13})/(g_2/g_3 \cdot A_{21}+A_{31}) \qquad 7).$$

When the laser beam is not applied, d/dt=0 in Equation 3) then,

$$n_{30}/n_{10} = R_{13}/(R_{31}+R_{32}) \qquad 8)$$

The ratio of the number of particles of the case that the laser beam is applied and the case of not applied at the n=3 level is obtained from Equation 7) and 8) and is

$$\frac{n_3}{n_{30}} = \frac{(R_{12}+R_{13})\,(A_{31}+A_{32})}{R_{13}\,(g_2/g_3 \cdot A_{21}+A_{31})} \qquad 9)$$

In the plasma, the term of loss $\langle\sigma_3 v_e\rangle n_e$ by collision excitation by the electron from the 3-level must be considered in Equation 8) and 9). Thus, Equation 8) and 9) are

$$\frac{n_{3n}}{n_{10}} = \frac{R_{13}}{A_{31} + A_{32} + \langle \sigma_3 v_e \rangle n_e} \qquad 8a)$$

$$\frac{n_3}{n_{30}} = \frac{(R_{12} + R_{13})\,(A_{31} + A_{32} + \langle \sigma_3 v_e \rangle n_e)}{R_{13}(g_2/g_3 \cdot A_{21} + A_{31} + \langle \sigma_3 v_e \rangle n_e)} \qquad 9a)$$

$\langle \sigma_3 v_e \rangle n_e$ is calculated by Reference 9) and is shown in Table 2. The R_{13}/R_{12} in the plasma in the range of the electron temperature of 100eV to 1000eV is about 0.18 (Reference 10). The increment of the hydrogen atom density at the n=3 level is

$$\Delta n_3 = n_3 - n_{30} = (n_3/n_{30} - 1)\, n_{30} \qquad 10)$$

and the relationships between Δn_3 and n_{10} is obtained as follows from Equation 8a) and 9a).

$$\Delta n_3 = \left\{ \frac{(1 + R_{13}/R_{12})(A_{31} + A_{32} + \langle \sigma_3 n_e \rangle n_e)}{(R_{13}/R_{12})(g_2/g_3 \cdot A_{21} + A_{31} + \langle \sigma_3 v_e \rangle n_e)} - 1 \right\}$$

$$\cdot \frac{R_{13}\, n_{10}}{A_{31} + A_{32} + \langle \sigma_3 v_e \rangle n_e} \qquad 11)$$

The variation of $\Delta n_3/n_{10}n_e$ for T_e with the parameter of n_e in the range of /6
$n_e=10^7$ to $10^{14}cm^{-3}$ is shown in Fig. 3. From the figure, it can be seen that $\Delta n_3/n_{10}n_e$ is about constant at T_e>0.4KeV.

Table 2 Excitation ratio by the collision process from 3-level ($\langle \sigma_3 v_e \rangle n_e$)

T_e \ n_e	10^{12} cm^{-3}	10^{13} cm^{-3}	10^{14} cm^{-3}
50 eV	$3.7 \cdot 10^6 s^{-1}$	$3.7 \cdot 10^7 s^{-1}$	$3.7 \cdot 10^8 s^{-1}$
100	5.2	5.2	5.2
200	7.4	7.4	7.4
400	10.4	10.4	10.4
600	12.7	12.7	12.7
800	14.8	14.8	14.8
1000	16.5	16.5	16.5

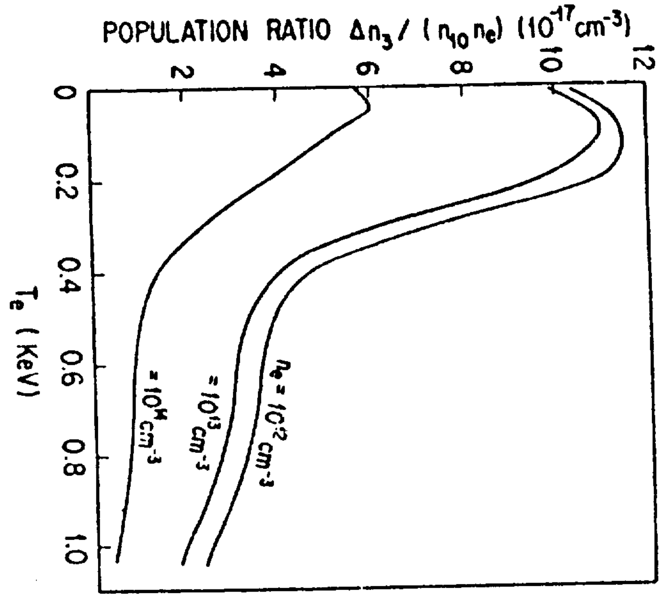

Fig. 3 Number of excitation particles for electron temperature ($n_{10}=10^7$ - 10^{14} cm^{-3})

2.3 Signal to Noise ratio (S/N) in tokamak plasma /7

This paragraph discusses the parameters for JFT-2M and JT-60 plasma. The background light is discussed in Appendix A.

1) S/N in the boundary layer

The following ranges are considered as the parameters of plasma.

$$n_{10} = 10^{10-14}\ cm^{-3},\quad n_e = 10^{12-13}\ cm^{-3},\quad T_e = 10-50\ eV,$$

$$V = 10\ cm^3,\quad \Delta\Omega = 8\cdot 10^{-3} sr,\quad \delta = 0.5$$

where V is fluorescent radiation volume, $\Delta\Omega$ is observation solid angle and δ is transmittance of filter for the H_α line. For instance, Δn_3 is obtained as $20\cdot10^6 cm^{-3}$ from Equation 11) or from Fig. 3 for the average values of n_{10} = $10^{10}cm^{-3}$, $n_e=2\cdot10^{12}cm^{-3}$ and T_e=10eV. In this fluorescence, the fluorescence entering the detector is

$$N_p/\tau = (\Delta n_3 A_{32})\,\Delta\Omega\cdot\delta/4\pi$$

$$= 3\cdot 10^{10} s^{-1}\,cm^{-3} \qquad 12)$$

When the oscillation time of the laser is $\tau = 5 \cdot 10^{-6}$s and the quantum efficiency of the detector is $\eta = 5\%$, the number of photo-electrons per pulse of the laser beam is

$$N_{pe} = 7.5 \cdot 10^{4} \qquad 13)$$

The number of photo-electrons of the background light per pulse is

$$N_{bpe} = 8 \cdot 10^{5} \qquad 14)$$

Thus the signal to noise ratio is

$$S/N = N_{pe} / \sqrt{N_{pe} + 2N_{bpe}} \qquad 15)$$

$$= 58$$

Therefore, there is no problem for measurement even though there is indeterminacy from not considering the emitted light intensity of the background light. However, the following items can be pointed out as methods to improve the S/N ratio.

1. Use the photomultiplier having the highest quantum efficiency.
2. The S/N increases with further distance from the inner wall of the vacuum vessel. (Decrease of n_{10} is small compared with increase of n_e and T_e.)

2) S/N in the plasma core

Next, the range of the plasma, hydrogen atom density $n_{10} = 10^{6-10}$ cm^{-3}, $n_e = 10^{13-14}$cm^{-3} and T_e = 1-10KeV is considered. As the standard, the plasma of $n_{10} = 10^{7}$cm^{-3}, $n_e = 5 \cdot 10^{13}$cm^{-3} and T_e = 1KeV is considered. In this case $\Delta n_3 = 6500$cm^{-3} and the number of photo-electrons, N_{pe} is 220. The background light is the same as Equation 14). /8

$$S/N = 0.2 \qquad 16)$$

The fluorescence measurement in the plasma core is under the limit but the measurement becomes possible by moving the measurement point from the plasma core so that n_{10} increases.

The following items can be pointed out as methods to make S/N>1.

1. Increase the diameter S_0 of the laser beam or lengthen the observation length to make the observation volume of fluorescence 10 times larger.
2. Perform the smoothing process with a high repetition laser oscillator (100Hz) rather than 1 pulse of laser beam.

3. The background light is emitted from the place of low T_e at the area near the plasma thus, the wave length is shifted from that of the core. Therefore, a filter can be used to shield the background light. The damping is around 1/3.

In the case that the smoothing process of item 2 is performed for 100ms, S/N is

$$S/N = 34 \qquad 17)$$

This indicates that measurement of hydrogen atom density is satisfactorily possible at the plasma core.

3) Calibration method (Reference 11)

As the calibration method, Rayleigh scattering with Ar gas or N_2 gas can be considered. When density of the filler gas is n_o, the number of photons of the incident laser beam is I_o $cm^{-2} \cdot s^{-1}$, the number of photons obtained from Rayleigh scattering is given by

$$\Phi_R = n_0 \sigma_R I_0 V \Delta\Omega / 4\pi \qquad 18)$$

When the increment of the hydrogen atom density excited to n=3 level is Δn_3, the number of photons Φ_F of fluorescence is given by

$$\Phi_F = \Delta n_3 A_{32} I_0 V \Delta\Omega / 4\pi \cdot \tau S_0 \qquad 19)$$

From Equation 18) and 19),

$$\Phi_F / \Phi_R = \Delta n_3 A_{32} / (n_0 \sigma_R) \cdot \tau S_0 \qquad 20)$$

Now, when the pulse duration of the laser beam is around 10ns and I_o of Equation 19) is replaced with $I_s\sqrt{I_o/I_s}$ (Reference 12) and when K is written as Equation 21),

$$K = n_0 \sigma_R / (\Phi_R A_{32} \sqrt{I_s} \tau S_0) \qquad 21)$$

Δn_3 is

$$\Delta n_3 = K \sqrt{I_0} \Phi_F \qquad 22)$$

The advantages and disadvantages of this method are as follows.

Advantages

1. High spatial resolution thus, accurate measurement of hydrogen atom density at the edge of the plasma is possible.
2. As the result of development of the laser oscillation apparatus having sufficient laser output and pulse duration, continuous variation of fluorescence /9

can be observed.

Disadvantages

1. Measurement of T_e and n_e is required besides measurement of the H_α line fluorescence.
2. Intensity of H_α line background light in the plasma dominates the value of S/N.
3. Components of non-thermal noise of the H_α line background light is important but it is not clear.
4. A viewing damper is required for elimination of stray light from the laser beam.

3. L_α line fluorescence from neutral hydrogen excited by dye laser /10

The laser beam with the wave length of the L_α line is obtained by converting the laser beam of 3645Å with krypton or beryllium gas to THG (Reference 3, 4, 13 to 15). XeCl excima laser excitation TMI dye laser oscillation apparatus is a laser oscillator for this purpose. The characteristics of this apparatus are output energy per pulse E=1.5 μJ(Po=10^{12}/pulse), $\tau = 5\ \mu s$, band width $\Delta\lambda = 10^{-2}$ Å, and about 20Hz of repetition (Reference 15). When the laser beam of flux Po is input into the optically thin gas, the absorbed power is

$$-dI/dt = (n_1 W_{12} - n_2 W_{21}) ch\nu$$
$$= (n_1 \cdot g_2/g_1 - n_2)\, c^3 g(\nu - \nu_0)\, P_0/(8\pi \nu^2 t_{spont}) \quad 23)$$

where W_{12} and W_{21} are induced excitation and induced emission ratio by laser beam respectively and are given as follows.

$$W_{12} = (g_2/g_1)\, W_{21}$$
$$W_{21} = c^3 P_0\, g(\nu - \nu_0)/(8\pi h \nu^3 t_{spont})$$

The actual emission spectral line is expressed with a Gaussian type or Lorentz's type. This emission beam of the $L\alpha$ line has Doppler shift due to the velocity distribution of the particles. When the gas is in an equilibrium state, the velocity distribution of the particles is Maxwellian velocity distribution and the frequency distribution of the emission beam is Gaussian type $g(\nu - \nu_0)$, i.e,

$$g(\nu-\nu_0)=2\sqrt{\ln 2}/\sqrt{\pi}\,\Delta\nu_D \cdot \exp\{-4(\ln 2)(\nu-\nu_0)^2/(\Delta\nu_D)^2\} \qquad 24)$$

where $\Delta\nu_D$ is full width at half maximum which is given as follows.

$$\Delta\nu_D=2\nu_0\sqrt{2kT_g\ln 2/Mc^2} \qquad 25)$$

This is the Doppler width. The relationships between the velocity of particles and the frequency is

$$\Delta\nu_D=\nu-\nu_0=v/c\cdot\nu_0 \qquad 26)$$

By measuring the broadening of spectrum $\Delta\nu_D$, the particle velocity V at the measuring point is obtained. Details of the particle velocity are not discussed in this report. Now, t_{spont} is related to oscillator strength f_{21} and is given as follows.

$$t_{spont}=m_e c^3/(8\pi^2 e^2\nu^2 f_{21}) \qquad 27)$$

When $T_g=4\cdot10^5$K, the Doppler width $\Delta\lambda_D$ is 0.55Å from $\Delta\lambda_D=-\lambda^2/c\cdot\Delta\nu_D$). With Equation 25) to 27) and with consideration of $n_1 \gg n_2$, Equation 23) is written as follows. /11

$$dI/dz=(8.3\cdot10^{-13}n_1 f_{21}\lambda_0^2 g_2 P_0/\Delta\lambda_D g_1 \cdot\exp\{-4(\ln 2)(\nu-\nu_0)^2/(\Delta\nu_D)^2\} \qquad 28)$$

where c dt = dz.

With $f_{21}=0.42$, $n_1dz=2\cdot10^{10}\text{cm}^{-2}$, $\Delta\lambda_D=0.55$Å, $\Delta\Omega=10^{-2}$sr, total transmittance of the optical system $T_r=0.12$ and quantum efficiency $\eta=0.15$ and since the absorption power of the laser beam is considered as the increment of fluorescence, the number of photoelectrons at the center (ν_0) of the spectral distribution is obtained by Equation 28) and is

$$N_{pe}=1800 \qquad 29)$$

On the other hand, with So=1cm^2, Tr=0.25 and $\tau=5\,\mu s$, the number of photoelectrons of the background light is 3750. Therefore, S/N is

$$S/N = 19 \qquad 30)$$

As can be found in Equation 28), the signal is proportional to n_1 and S/N is proportional to $\sqrt{n_1}$. The previously mentioned Rayleigh scattering can be used for the calibration.

The following advantages and disadvantages can be pointed out for this method.

Advantages

1. The velocity distribution function of the hydrogen atom can be obtained by measuring the spectral distribution.
2. The measured results are not related to n_e and T_e.

Disadvantage

1. The most sophisticated laser oscillator is required. Table 3 shows the present status of laser oscillators for LIFM.

1- 種類	5- 励起用レーザー発振装置	11- 出力エネルギー	13- 色素レーザー	14- 波長	17- パルス幅	19- 最大繰返し数
2- 固体	6- YAGレーザー	700 mJ	o	15- 可視	8～9ns	100 Hz
3- 液体	----------→	12- 200 mJ (色素レーザー出力)	o	15- 可視	1～5 μs	20 Hz
4- 気体	7- エキシマレーザー	400 mJ	o	15- 可視	15 ns	250 Hz
	8- N_2 レーザー	4～10mJ	o	15- 可視	50ps～10ns	50 Hz
	9- Ar（クリプトン）レーザー	18 W	o	15- 可視	----→	cw
	10- Ar_2^*（又はArF^*）レーザー	300 mJ	----→	16- 紫外	18- 開発中	～100 Hz

20- 注：可視光はSHG（2倍高調波発生）用結晶又はTHG（3倍高調波発生）用気体により紫外光に変換できる。

Table 3 Present status of laser oscillators for LIFM /12

1- Type
2- Solid
3- Liquid
4- Gas
5- Excitation laser oscillator
6-YAG laser
7-Excima laser
8- N_2 laser
9-Ar(Krypton) laser
10-Ar_2*(or ArF*) laser
11- Output energy
12- (Dye laser output)
13- Dye laser
14- Wave length
15- Visible
16- Ultraviolet
17- Pulse duration
18- Under development
19- Maximum cycles
20- Note : Visible light can be converted to ultraviolet by the crystal for SHG (generation of double harmonics) or the gas for THG (generation of triple harmonics).

4. H_α line fluorescence obtained by resonant excitation into n=1 → 2 level /13

The fluorescence of the H_α line spectrum emitted due to the transition from the n=3 to 2 is measured when the excitation into the n=1 → 2 level occurred with the laser beam oscillated by the L_α line. The absorption power of the laser beam is previously mentioned in Equation 23). When the laser beam is being absorbed, the number of H_α line photons emitted per second is obtained from Equation 2) and is as follows.

$$\Delta n_3 A_{32} = R_{12} n_1 / (g_2/g_3 \cdot A_{21}/A_{32} + 1) \qquad 31)$$

where $n_2 = -g_2/g_3 \cdot n_3 \exp(h\nu/kTg)$ and $h\nu \ll kTg$. For n=3S, 3P and 3D level, the electrons are distributed like a statistical distribution. Even in the case that only the 3S and 3D level are excited, the slippage from Equation 31) can be ignored (Reference 16). $R_{12}n_1$ in Equation 31) equals the fluorescence of the L_α line emitted from the incidence of the laser beam oscillated with the wave length of the L_α line. The number of photons of the H_α line spectrum is 0.17 times $((=g_2/g_3 \cdot A_{21}/A_{32}+1)^{-1})$ less than the number of photons of the $L\alpha$ line. The quantum efficiency of the detector η=0.1 in the case of the $H\alpha$ line while η =0.15 in the case of the $L\alpha$ line. But the transmittance of the observation system is twice more for the wave length of the H_α line. Therefore, the number of the detected H_α line photons is 400 compared with the previously mentioned 1800. In a similar manner, the number of photoelectrons obtained of the background light is 860 thus, S/N is

$$S/N = 9 \qquad 32)$$

Therefore, the measurement by this method is possible. The following item can be pointed out as the advantage of this method.

1. The H_α line is less influenced by the optical parts than the L_α line thus the longer optical path can be used which makes the magnetic shield easy.

5. Application to tokamak plasma /14

This chapter discusses some points at issue in the case that the laser induced fluorescence method is applied to the JFT-2M and JT-60 tokamaks of the Japan Atomic Energy Research Institute.

5.1 $H\alpha$ line fluoresence in plasma boundary

When the neutral hydrogen atom density is obtained from the measurement of the $H\alpha$ line fluoresence, measurement of the electron temperature and density is required. As the measurement apparatus for the above data, a Thomson scattering measurement device and a probe measurement device are used. This equipment is the established equipment for measurement so there is no problem for a general experiment. Fig.4 (a) and (b) shows the arrangement which can measure the $H\alpha$ line spectrum using the JFT-2M and the JT-60. In the figures, the measurement arrangement of the $L\alpha$ line spectrum is also shown. In Fig.4(a), THG is located in a lower position so that it is off the path of the incident laser beam and in Fig.4(b), the path of the laser beam in which the laser beam goes from bottom to top is adapted. For the light receiving system, the optical system written "$H\alpha$" is used.

The output beam diameter of the laser oscillator is 5 x 5 mm^2; it is magnified 4 times to 20 x 20 mm^2 with the lens with focal length f=120cm. To reduce the stray light, pin holes are made at the focal point of the lens. The diameter of the laser at the upper or lower port of the tokamak apparatus is about 3 cm. The observation volume of fluorescence is about 10 cm^3 and is measured from the side (It is interesting to measure in the same direction but it requires more studies ,thus it will be studied in the future.). A viewing damper and laser beam damper are also installed to reduce the stray light. This influences the S/N significantly,but this technique has been established for the Thomson scattering equipment (Reference 17). To improve the S/N, the collecting lens is located as close as possible to the plasma to increase the observation solid angle and it is desired that the diameter of the lens or mirror is about 20 cm. With this lens, fluorescence of the $H\alpha$ line is collected on the filter (Band width: about 20 Å) and it is guided to the photomultiplier with the optical fiber. (The location of the filter and the optical fiber can be reversed.) The photomultiplier has to be located far from the tokamak equipment and also it has to be sufficiently magnetically shielded so that it is not influenced by the magnetic field. This technique has also been established with the Thomson scattering equipment (Reference 16). As an example, the characteristics of the laser beam that fit this measurement are $\tau = 5\,\mu s$, P=5kW/Å, $\Delta\lambda = 10$ Å, E=250mJ/pulse and the cycle is more than 10Hz.

5.2 H_α line fluorescence in plasma core

In the case that the hydrogen atom density in the plasma core is more than about $10^7 cm^{-3}$, n_1 can be determined by measuring the fluorescence. The optical system is the same as the one mentioned in paragraph 5.1. The characteristics of the laser beam that fit this measurement are $\tau = 5\,\mu s$ $P = 50\,kW/\mathring{A}$, $\Delta\lambda > 20\,\mathring{A}$, $E = 5J/pulse$ and the cycle is more than 10Hz. This kind of laser oscillator belongs to the highest class oscillators at the present time.

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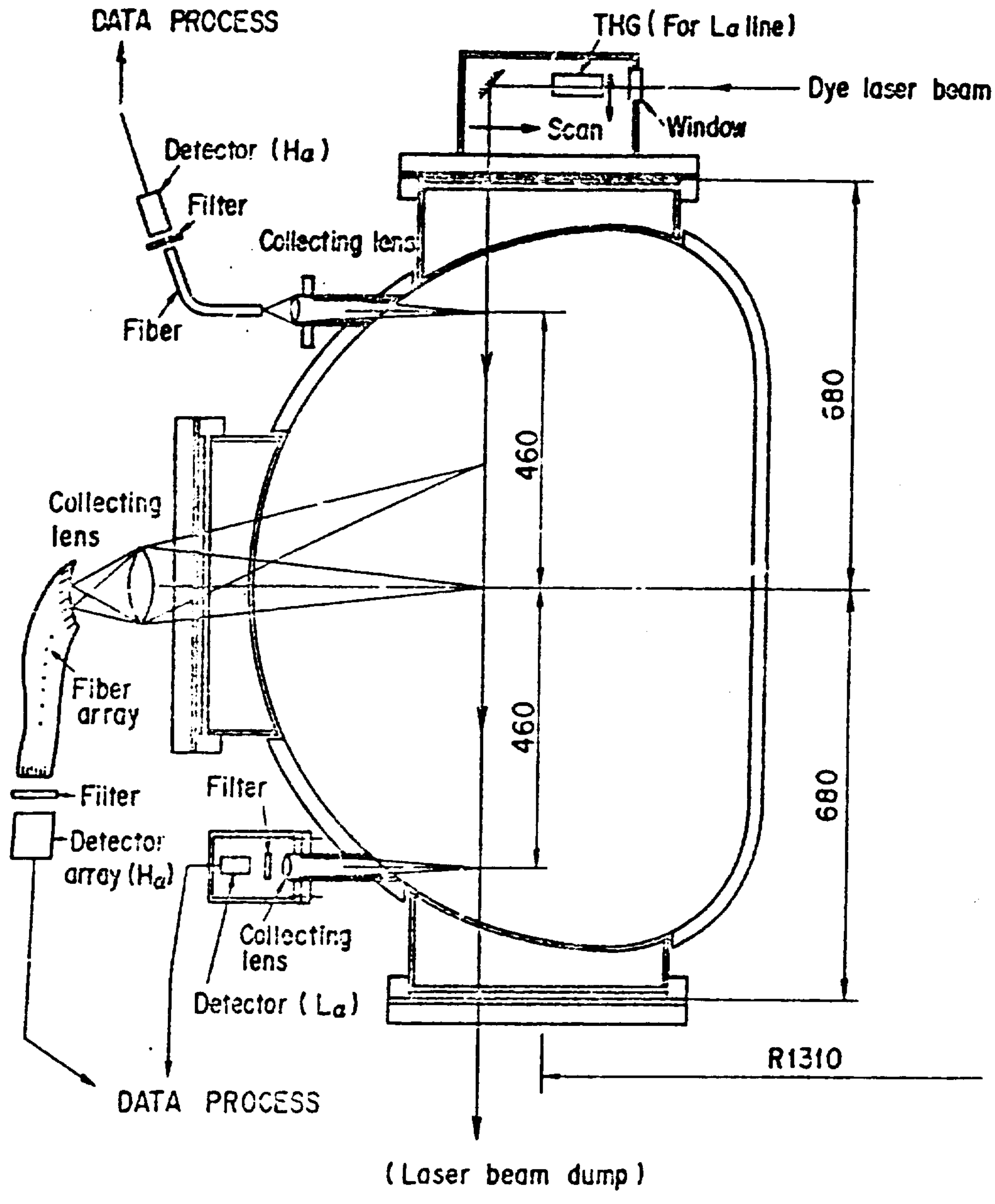

Fig. 4(a) Optical path for Hα and Lα line fluorescence with JET-2M

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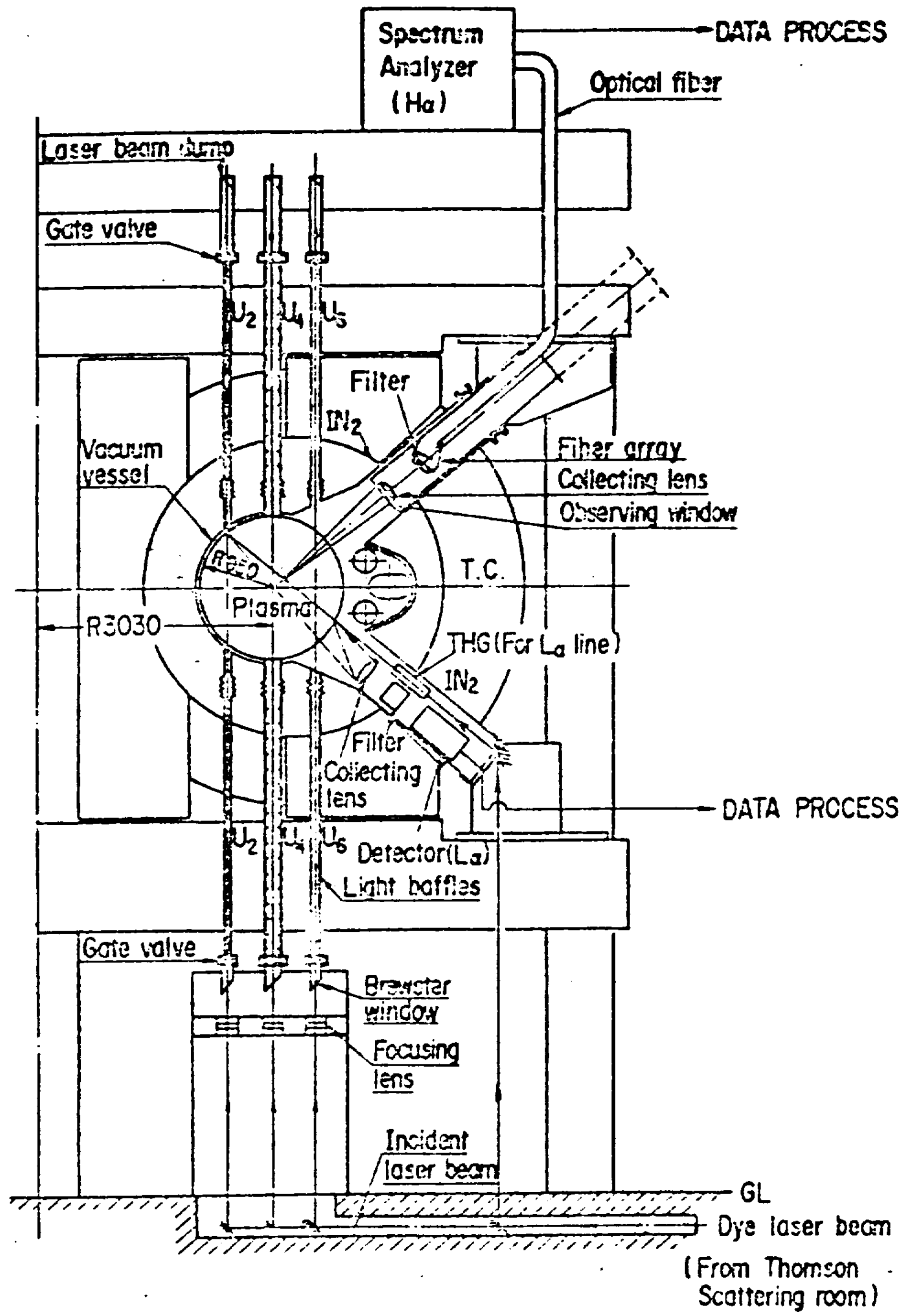

(b) Optical path for H_α and L_α fluorescence with JT-60

5.3 L_α line fluorescence

When the hydrogen atom density is determined by measuring the $L\alpha$ line fluorescence, measurement of the electron temperature and density is not required. The optical system is the same as the system for measurement of $H\alpha$ line fluorescence except the laser oscillator, window, lens, filter and detector. The produceable diameter of the collecting lens of the laser beam (3235Å) and the incident window is around 3cm when LiF or MgF_2 is used for the glass material. The incident laser beam is transformed to the triple harmonics with the gas (krypton gas cell and etc.) for the triple harmonics generation (THG) in the vessel. Examples of the optical system are shown in Fig. 4(a) and (b). The optical system in the IN_2 port is used in the system shown in Fig. 4(b). The optical system written with $L\alpha$ in Fig. 4(a) and (b) is used for the light receiving system. In this system, the observing system is important; i.e, when the system uses about 10^{-2}sr of solid angle, the produceability of the satisfactory LiF lens has to be considered. Also the reflection system of the mirror has to be considered besides the lens, but this is not discussed here and it will be a future study.

Some photomultipliers have CsI (used at less than 1950Å) or KBr (used at less than 1700Å) on the cathode screen and the occurrence of absorption of oxygen on the surface of the photomultiplier in the vessel is considered. This plays a role as a filter for $L\alpha$ line fluorescence. Usually the oxygen absorption cells are installed as the filter. The excima excitation dye laser oscillator has a 35 mJ/pulse of the fundamental wave output (3647Å) and 10^{12} ($1.6 \cdot 10^{-3}$mJ) of photons are obtained at the triple harmonics output (1215Å) after passing the Kr-Ar mixture gas.

5.4 H_α line fluorescence from neutral hydrogen excited simultaneously by dye lasers with $H\alpha$ or L_α lines

To eliminate problems occuring in the observation system for $L\alpha$ line fluorescence observation as mentioned previously, similtaneous excitation of neutral hydrogen atoms by the laser beam with the $L\alpha$ or $H\alpha$ lines is considered. Incidence of the laser beams with the $H\alpha$ line and the $L\alpha$ line to the tokamak apparatus with the coaxial optical system is required. Thus, matching of the laser apparatus is necessary and it would be complex. However, when it is necessary to disconnect the detector from the tokamak apparatus, adaption of this measurement system should be considered.

6. Conclusion

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It is possible to obtain the neutral hydrogen atom density by applying the fluorescence measurement method to regular tokamak plasma with resonance excitation of the H_α line. This method has the strong point of spacial resolution compared with the natural emitted light measurement method of the H_α line but calculation of the neutral hydrogen atom density requires the electron temperature, T_e and the electron density, n_e and accuracy of these is important. In the case of less than $n_o=10^5 cm^{-3}$, the measurement of the hydrogen atom density and the velocity distribution at the plasma core is difficult.

In the L_α line fluorescence measurement, the optical parts used are small thus accurate measurement of the hydrogen atom density and the velocity distribution in the shadow of the limiter is obtained. However, a long optical path in vacuum conditions should be avoided because of consideration of the light receiving solid angle and the self absorption of the optical parts. The simultaneous resonance excitation by the L_α line and H_α line laser beam solves this problem.

Acknowledgement

The authors cordially thank Toshi Kasai, Hideaki Yokomizo (The critical plasma measurement development group) and Tooru Matoba of the research staff for their advice from the stand point of spectroscopy and thank Professor E. Hintz, Dr. P. Bogen and Dr. H. Schweer in the Urich KFA Institute in West Germany, and also Akimasa Funabashi, the chief of the plasma laboratory, Yasuo Suzuki, the chief of the critical plasma measurement development group, Masatoshi Tanaka, the chief of the nuclear fusion research department, Tsutomu Iijima, the chief of the JT-60 laboratory, Mitsuji Yoshiikawa, the chief of the critical plasma research group, Akira Tomaji, the chief of the Naka Institute and Shigeru Mori, the vice chairman.

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Appendix A: Intensity estimation of background light in tokamak plasma /20

The background light which becomes the noise component for measurement of the hydrogen atom is mainly the emission light from the hydrogen atoms surrounding the plasma. The velocity distribution of the hydrogen atoms surrounding the plasma is the Maxwellian velocity distribution. The slow velocity component of the distribution is T_g=1eV and the fast velocity component is T_g=30eV and close to the Gaussian type. When the particles which enter the plasma are considered with the fast component only, the average velocity of the particles toward the plasma core is

$$\bar{v}_g = 2/\sqrt{\pi} v_0 \int_0^\infty v_g \exp\{-(v_g/v_0)^2\} dv$$
$$= \sqrt{2}/\pi \sqrt{kT_g/M} = 4 \cdot 10^6 \text{ cm/s}$$

where M is mass of the hydrogen atom. For instance in the case of the hydrogen atom density $n_0=10^{10}cm^{-3}$, half enter the plasma core and the other half is considered to be returned to the wall and in this case, the particle flux is $n_0\bar{v}_g/2=2\cdot10^{16}cm^{-2}\cdot S^{-1}$. In this particle flux, some of them are ionized or turn toward the wall from the plasma core caused by the charge exchange recombination. If the coefficient is 2, the particle flux locked in the plasma by ionization is $1\cdot10^{16}cm^{-2}\cdot S^{-1}$. The ratio of excitation of hydrogen atoms and the ionization ratio are proportional and the ratio is 0.8 for the $L\alpha$ line radiation intensity and 10 for the $H\alpha$ line radiation intensity. In the observation in the horizontal direction, the background light is radiated in 4π space in all ranges. Thus the background light radiation intensity is $1.6\cdot10^{14}sr^{-1}cm^{-2}s^{-1}$ against the $H\alpha$ line radiation light and $2\cdot10^{15}sr^{-1}cm^{-2}s^{-1}$ against the $L\alpha$ line radiation light. The variation of number of the radiation photons $n_{H\alpha}$ and $n_{L\alpha}$ of the $H\alpha$ line and the $L\alpha$ line against T_g is shown in Fig.5.

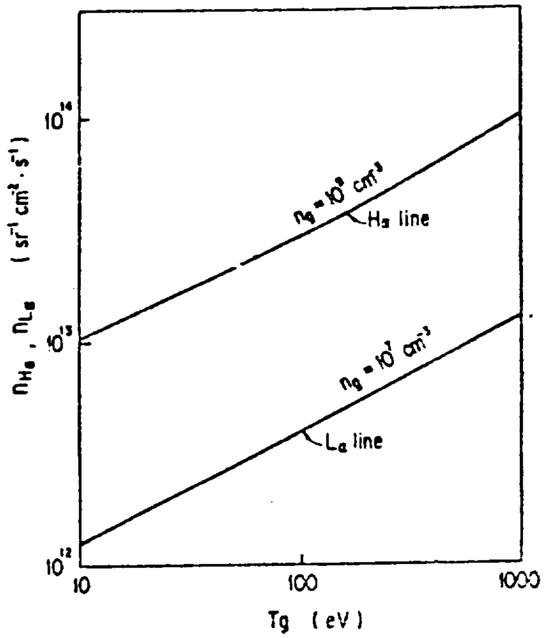

Fig.5 Number of photons of H_α and L_α radiation light for hydrogen atom temperature

($n_{H\alpha}$ and $n_{L\alpha}$ are in proportion to n_g)

Appendix B: Zeeman effect and polarization /21

The atom with the electron with the resultant spin quantum number S=0 is emitted in the magnetic field. In this case, the spectrum of the atom changes due to effects of the magnetic field. The spectral line by the Zeeman effect is the light emitted when the transition in the different levels of the total angular momentum J of the electron in the atom occurs and the frequency is shifted $\Delta\nu$ to both sides of the frequency in the case of no existence of the magnetic field H.

$$\Delta\nu = \pm g\,\mu_B H/h$$

where g is the Lande's factor and μ_B is the Bohr magneton.

When it is assumed that the magnetic field at the outer boundary of tokamak plasma is less than 2.5T. The split of the fluorescence by the magnetic field of 2.5T is the result from the split of the σ component of the normal Zeeman effect and it is ± 0.017Å for the fluorescence of the L_α line and ±0.5Å for the fluorescence of the H_α line. The split space of the σ component equals the Doppler broadening $\Delta\lambda_D$ observed at T_g=4eV for the H_α line and at T_g=0.13eV for the L_α line. On the other hand, the split is very small, about 0.15Å for the H_α line and about 0.0054 Å for the L_α line when the π component is excited by the polarized laser beam. Therefore in either case, the split for the fluorescence of the L_α line is very small and the effect on the measurement results of the spectral distribution can be ignored.

Also the Zeeman effect effects the polarization characteristics of fluorescence and the angle distribution of radiation. When the magnetic field is 2.5T and S<<1, the polarization of the fluorescence of the L_α line approximately equals the polarization for the normal Zeeman triplet level. i.e, when the laser beam is injected in the plasma in the same direction as the π polarized light, the fluorescence is polarized. When the π component of 90° against the polarization plane of the laser beam is observed, the intensity of fluorescence increases 1.5 times compared with the other cases. This is because the hydrogen atom is not radiated in the direction of the magnetic field.

However, it should be noticed that the fluorescence of the H_α line is a little polarized. When S>>1, the fluorescence of the hydrogen atom is radiated isotropically and the polarization characteristics disappear.

International System of Units (SI) and conversion chart

Table 1 SI fundamental unit and supplementary unit

1- 量	2- 名称	3- 記号
4- 長さ	13- メートル	m
5- 質量	14- キログラム	kg
6- 時間	15- 秒	s
7- 電流	16- アンペア	A
8- 熱力学温度	17- ケルビン	K
9- 物質量	18- モル	mol
10- 光度	19- カンデラ	cd
11- 平面角	20- ラジアン	rad
12- 立体角	21- ステラジアン	sr

1- Quantity
2- Names
3- Symbols
4- Length
5- Mass
6- Time
7- Electric Current
8- Thermodynamic Temperature
9- Gram Molecule
10- Luminous Intensity
11- Plane Angle
12- Solid Angle
13- Meter
14- Kilogram
15- Second
16- Ampere
17- Kelvin
18- Mol
19- Candela
20- Radian
21- Steradian

Table 2 Units used together with SI

1- 名称	8- 記号
2- 分，時，日	min, h, d
3- 度，分，秒	°, ′, ″
4- リットル	l, L
5- トン	t
6- 電子ボルト	eV
7- 原子質量単位	u

1 eV = 1.60218×10^{-19} J
1 u = 1.66054×10^{-27} kg

1- Name
2- Minute, Hour, Day
3- Degree, Minute, Second
4- Liter
5- Ton
6- Electron Volt
7- Atomic Mass Unit
8- Symbol

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Table 3 Derived unit having characteristic name

1- 量	2- 名称	3- 記号	4- 他のSI単位による表現
5- 周波数	24- ヘルツ	Hz	s^{-1}
6- 力	25- ニュートン	N	$m \cdot kg/s^2$
7- 圧力、応力	26- パスカル	Pa	N/m^2
8- エネルギー、仕事、熱量	27- ジュール	J	$N \cdot m$
9- 工率、放射束	28- ワット	W	J/s
10- 電気量、電荷	29- クーロン	C	$A \cdot s$
11- 電位、電圧、起電力	30- ボルト	V	W/A
12- 静電容量	31- ファラド	F	C/V
13- 電気抵抗	32- オーム	Ω	V/A
14- コンダクタンス	33- ジーメンス	S	A/V
15- 磁束	34- ウェーバ	Wb	$V \cdot s$
16- 磁束密度	35- テスラ	T	Wb/m^2
17- インダクタンス	36- ヘンリー	H	Wb/A
18- セルシウス温度	37- セルシウス度	℃	
19- 光束	38- ルーメン	lm	$cd \cdot sr$
20- 照度	39- ルクス	lx	lm/m^2
21- 放射能	40- ベクレル	Bq	s^{-1}
22- 吸収線量	41- グレイ	Gy	J/kg
23- 線量当量	42- シーベルト	Sv	J/kg

1- Quantity
2- Name
3- Symbol
4- Expression with other SI units
5- Frequency
6- Force
7- Pressure, Stress
8- Energy, Work, Quantity of heat
9- Power, radiation flux
10- Quantity of electricity, Electric charge
11- Electric potential, Voltage, Electromotive force
12- Electrostatic capacity
13- Electric resistivity
14- Conductance
15- Magnetic flux
16- Magnetic flux density
17- Inductance
18- Celsius temperature
19- Luminous flux
20- Luminance
21- Radioactivity
22- Absorbed dose
23- Duse equivalent
24- hertz
25- newton
26- pascal
27- joule
28- watt
29- coulomb
30- volt
31- farad
32- ohm
33- siemens
34- weber
35- tesla
36- henry
37- Degree celsius
38- lumen
39- lux
40- becquerel
41- gray
42- sievert

Table 4 Units provisionally maintained with SI

1- 名称	2- 記号
3- オングストローム	Å
4- バーン	b
5- バール	bar
6- ガル	Gal
7- キュリー	Ci
8- レントゲン	R
9- ラド	rad
10- レム	rem

1 Å = 0.1 nm = 10^{-10} m

1 b = 100 fm^2 = 10^{-28} m^2

1 bar = 0.1 MPa = 10^5 Pa

1 Gal = 1 cm/s^2 = 10^{-2} m/s^2

1 Ci = 3.7×10^{10} Bq

1 R = 2.58×10^{-4} C/kg

1 rad = 1 cGy = 10^{-2} Gy

1 rem = 1 cSv = 10^{-2} Sv

1- Name 2- Symbol 3- angstrom

4- barn 5- bar 6- gal

7- curie 8- roentgen 9- rad

10- rem

Table 5 Si Prefix

1- 倍数	2- 接頭語	3- 記号
10^{18}	4- エクサ	E
10^{15}	5- ペタ	P
10^{12}	6- テラ	T
10^{9}	7- ギガ	G
10^{6}	8- メガ	M
10^{3}	9- キロ	k
10^{2}	10- ヘクト	h
10^{1}	11- デカ	da
10^{-1}	12- デシ	d
10^{-2}	13- センチ	c
10^{-3}	14- ミリ	m
10^{-6}	15- マイクロ	μ
10^{-9}	16- ナノ	n
10^{-12}	17- ピコ	p
10^{-15}	18- フェムト	f
10^{-18}	19- アト	a

1- Multiple
2- Prefix
3- Symbol
4- exa
5- peta
6- tera
7- giga
8- mega
9- kilo
10- hecto
11- deca
12- deci
13- centi
14- milli
15- micro
16- nano
17- pico
18- femto
19- atto

(Note)

1. Table 1 to 5 are according to "International System of Units" Edition No. 5 in 1985 by the International Committee of Weights and Measures except the values of 1eV and 1u are according to CODATA of 1986.
2. Table 4 should include nautical mile, knot, are and hectare but were omitted in this paper.
3. The "bar" is classified in the category of Table 2 in JIS only in the case that it indicates pressure of fluid.
4. The "bar", "barn" and the unit for blood pressure "mmHg" are classified in the category of Table 2 according to the EC Cabinet board of directors.

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1– 力

N (=10^5 dyn)	kgf	lbf
1	0.101972	0.224809
9.80665	1	2.20462
4.44822	0.453592	1

2– 粘度 1 Pa·s (N·s/m²) = 10 P (ポアズ) (g/(cm·s))

3– 動粘度 1 m²/s = 10⁴ St (ストークス) (cm²/s)

4– 圧力

MPa (=10 bar)	kgf/cm²	atm	mmHg (Torr)	lbf/in² (psi)
1	10.1972	9.86923	$7.50062 \times 10^{[illegible]}$	145.038
0.0980665	1	0.967841	735.559	14.2233
0.101325	1.03323	1	760	14.6959
$1.33322 \times 10^{[illegible]}$	$1.35951 \times 10^{[illegible]}$	$1.31579 \times 10^{[illegible]}$	1	$1.93368 \times 10^{[illegible]}$
$6.89476 \times 10^{[illegible]}$	$7.03070 \times 10^{[illegible]}$	$6.80460 \times 10^{[illegible]}$	51.7149	1

5– エネルギー・仕事・熱量

J (=10^7 erg)	kgf·m	kW·h	6– cal (計量法)	Btu	ft·lbf	eV
1	0.101972	$2.77778 \times 10^{[illegible]}$	0.238889	$9.47813 \times 10^{[illegible]}$	0.737562	$6.24150 \times 10^{[illegible]}$
9.80665	1	$2.72407 \times 10^{[illegible]}$	2.34270	$9.29487 \times 10^{[illegible]}$	7.23301	$6.12082 \times 10^{[illegible]}$
$3.6 \times 10^{[illegible]}$	$3.67098 \times 10^{[illegible]}$	1	$8.59999 \times 10^{[illegible]}$	3412.13	$2.65522 \times 10^{[illegible]}$	$2.24694 \times 10^{[illegible]}$
4.18605	0.426858	$1.16279 \times 10^{[illegible]}$	1	$3.96759 \times 10^{[illegible]}$	3.08747	$2.61272 \times 10^{[illegible]}$
1055.06	107.586	$2.93072 \times 10^{[illegible]}$	252.042	1	778.172	$6.58515 \times 10^{[illegible]}$
1.35582	0.138255	$3.76616 \times 10^{[illegible]}$	0.323890	$1.28506 \times 10^{[illegible]}$	1	$8.46233 \times 10^{[illegible]}$
$1.60218 \times 10^{[illegible]}$	$1.63377 \times 10^{[illegible]}$	$4.45050 \times 10^{[illegible]}$	$3.82743 \times 10^{[illegible]}$	$1.51857 \times 10^{[illegible]}$	$1.18171 \times 10^{[illegible]}$	1

7– 1 cal = 4.18605 J (計量法)
= 4.184 J (熱化学)
= 4.1855 J (15 °C)
= 4.1868 J (国際蒸気表)

8– 仕事率 1 PS (仏馬力)
= 75 kgf·m/s
= 735.499 W

9– 放射能

Bq	Ci
1	$2.70270 \times 10^{[illegible]}$
$3.7 \times 10^{[illegible]}$	1

10– 吸収線量

Gy	rad
1	100
0.01	1

11– 照射線量

C/kg	R
1	3876
$2.58 \times 10^{[illegible]}$	1

12– 線量当量

Sv	rem
1	100
0.01	1

13– (86年12月26日現在)

Conversion Chart

1– Force

2– Viscosity 1 Pa-s(N·s/mm²)=10P(poise)(g^f(cm·s))

3– Kinematic viscosity 1 m²/s=10⁶s(Stokes)(cm²/s)

4– Pressure

5– Energy, Work, Quantity of heat

6– cal (Weight and Measure Act)

7– 1 cal=4.18605 J (Weight and Measure Act)
=4.184 J (Thermochemistry)
=4.1855 J (15°C)
=4.1868 J (International Steam Table)

8– Power= 1 ps (power)
=75 Kgf·m/s
=725.499 w

9– Radioactivity

10– Absorbed dose

11– Exposure

12– Duse equivalent

13– (As of December 26, 1986)

Report Documentation Page

National Aeronautics and Space Administration

1. Report No. TT-20331	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle DESIGN STUDY FOR MEASUREMENT OF NEUTRAL HYDROGEN ATOM DENSITY BY LASER INDUCED FLUORESCENCE METHOD		5. Report Date SEPTEMBER 1988
		6. Performing Organization Code
7. Author(s) Toshihiko Yamauchi, Hiroaki Ogawa, Reiji Yamada and Takeshi Fukuda		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Washington, DC 20546		11. Contract or Grant No. NASW-4307
		13. Type of Report and Period Covered translation
12. Sponsoring Agency Name and Address NASA - LEWIS RESEARCH CENTER		14. Sponsoring Agency Code

15. Supplementary Notes

Transl. from JAPANESE to ENGLISH. Japan Atomic Energy Research Institute, March, 1987, 25 pgs., JAERI-M-87-045

Transl. by SCITRAN, Santa Barbara, CA 93150.

16. Abstract

It is designed to measure the fluorescence light emitted from the transitions 1S-2P of L sub alpha line (lambda = 1215 A) or 2P-2S or 2P-3D of H sub alpha line (lambda = 6563 A), excited by the laser induced fluorescence method. The signal-to-noise ratio (S/N) is evaluated at the measurement in the parameter (n-bar sub e = 10 sup 12-10 sup 14 cm sup. -3, T sub e = 10 eV - 1 KeV) of tokamak plasma. The light paths in JFT-2M and JT-60 tokamaks are proposed.

17. Key Words (Suggested by Author(s))	18. Distribution Statement unclassified-unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
unclassified	unclassified	37	

NASA FORM 1626 OCT 86